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THE MAGNETIC ROTATORY
DISPERSION
OF
SODIUM VAPOR.

By

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DISSERTATION

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INTRODUCTION.

In 1811 Arago[1] discovered that rotation of the plane of polarization occurs when plane polarized light is transmitted through quartz in the direction of its optic axis. This was followed by the careful investigations of Biot[2] which led him to the deduction of his three well-known laws. That the phenomenon was not confined to solids alone but occurred also with liquids and gases, was soon made evident by the work of Biot, Sir. J. Herschel, Brewster, Faraday and others. Then followed Faraday's[3] discovery that the plane of polarization is rotated also by a magnetic field.

After the discovery by Fox Talbot[4] about 1840, of the existence of anomalous dispersion, this phenomenon was looked for in the rotatory dispersion of optically-active substances. Biot[5], Arndtsen[6], Landolt[7], Masini and Gennari[8], Cotton[9] and

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[1] Arago, Oeuvres Completes, tom. X, p. 35, 1812.
[2] Biot, Ann. de Chimie et de Physique, 1815.
[3] Faraday, Experimental Researches (XIX th series), vol. III, p. 1; Phil. Trans. p. 1, 1846.
[4] Talbot, see Tait's Light 196, and Proc. Roy. Soc. Edinburgh, 1870-71.
[5] Biot, Ann. de Chimie et de Physique, (3) 10, p. 5, 1844.
[6] Arndtsen, Ann. de Chimie et de Physique, (3) 54, p. 403, 1858.
[7] Landolt, Beibl. 5, p. 298, 1881.
[8] Masini and Gennari, Zeitschr. fur phys. Chemie. 19, p. 113, 1896.
[9] Cotton, Ann. de Chimie et de Physique, (7) 8, p. 347, 1876.

others observed anomalous rotatory dispersion in various naturally active liquids.

It was natural to expect that this anomaly might possibly exist in magnetically-active substances also; several investigators have studied various substances with results not altogether concordant. Becquerel[10] in 1880 observed the effect in oxygen but others have been unable to confirm his results. Macaluso and Corbino[11] worked with sodium vapor and found that the rotation was positive, and abnormally great, on each side of the D absorption band, but had a small positive value inside the band. Zeeman[12] also, with a flame between magnet poles, investigated the rotation with quite rare vapor in the vicinity of the D lines and obtained a positive rotation just outside the two D lines and a very great negative rotation inside each of them. Cotton[13] found an apparent anomalous rotation in ferric-chloride, cupric-acetate and other liquids. He found with a solution of a substance with which he could measure on only one side of the absorption band of the substance, that on approaching the absorption band from the red towards the violet, the rotation was greater than the value for the

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[10] Becquerel, Compt. Rend. 90, p. 1407, 1880.
[11] Macaluso and Corbino, Compt. Rend. 127, p. 548, 1898.
[12] Zeeman, Proc. Roy. Acad. of Amsterdam, 1902.
[13] Cotton, L'eclair electr. 8, p. 162 and 169, 1896.

solvent alone. Then with a solution of another substance with which he could approach the absorption band from the violet towards the red, he found a rotation smaller than the value for the solvent alone. From this he concluded that for both of the dissolved substances, the rotatory dispersion curve was of the same type as the ordinary anomalous dispersion curve. He did not determine the curve for both sides of the same absorption band nor did he measure the rotation inside the band.

In 1900, Schmauss[14] worked with very thin alcoholic solutions of fuchsin, cyanin, naphthalin-red and eosin and didymium glass. The greatest concentrations by weight varied from 0.000004 to 0.000024. All of his curves show a maximum and a minimum point at each absorption band and are similar to the curves for ordinary anomalous dispersion. He later[15] investigated liquid oxygen and solutions of aniline-blue, litmus and three of the rare earths. His results show that, (1) the anomalous effects increase with increasing concentration, (2) the maximum rotation is independent of the field strength and (3) the negative rotation inside the absorption band decreases with increasing field.

Bates[16] has been unable to confirm the work of Schmauss.

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[14]. Schmauss, Ann. d. Phys. 2, p. 280, 1900.
[15]. Schmauss, Ann. d. Phys. 8, p. 842, 1902; 10, p. 853, 1903.
[16]. Bates, Ann. d. Phys. 12, p. 109, 1903.

with alcoholic solutions of fuchsin and cyanin and aqueous solutions of aniline-blue and litmus in a very sensitive apparatus, he found no anomaly whatsoever .

In the light of these apparently contradictory results, it seemed as though more work should be done to endeavor to obtain further evidence on the question and it was with this object in view that the present experiment was undertaken. Hitherto the experiments with sodium vapor have in general, been made with sodium salts in flames. These comparatively rare vapors have confined the observations to the very immediate vicinity of the D lines. By employing much denser vapors, it has been found possible, as will be shown in this paper, to measure the magnetic rotation over a much wider range on each side of the D lines and to show that the absorption bands in the red and blue have also a very great effect on the rotation.

APPARATUS AND METHOD.

The sodium vapor obtained by heating some sodium salt in a flame is necessarily very rare, and with such a vapor, as is well known, the rotation only very near the D lines is perceptible. In order to obtain greater rotations it is obvious that denser vapor must be employed. This was accomplished by heating with a Bunsen flame, pure sodium in an exhausted glass tube. This tube of hard Jena glass had a length of 25 cm. and an inside diameter of 1.3 cm. Over this and occupying a position midway between the ends of the glass tube was a brass tube 8.2 cm. in length and of such a diameter that it would just slide easily on the glass tube. A solid cylindrical piece of pure sodium of the same length as this brass tube and having a diameter of 0.6 cm. was prepared in the following way. A good-sized piece of sodium was selected and after being dried off with filter paper, a piece was cut out of the interior of this and then melted for several minutes in an iron crucible over a Bunsen flame. The occluded gases having thus been driven off, the molten metal was poured into an iron cylinder. This cylinder had a tight fitting iron piston which,

when pressed in by squeezing in a vise, forced the sodium out through a small hole in the end and the desired length was then cut off. This sodium stick was then placed in the centre of the glass tube as quickly as possible to prevent the moist air coming in contact with it, and the ends of the tube closed with thin pieces of glass, cemented on. These glass ends were first made from microscope cover glasses but these were so thin that they became doubly-refracting when the tube was exhausted and the ends were after this made from microscope slides. These glass ends were tested in the magnetic field employed for the experiment, but no rotation due to them could be detected. The cement was mixed with lamp-black to prevent undesirable light being transmitted through the glass itself of the tube.

Directly over the sodium and inside the glass tube was a thermo-element made of iron and constantin fused together; the ends from this passed out through a fine glass tube at one end of the sodium tube. Passing through the other end was a tube of small diameter which was connected to an air-pump and sealed off after exhausting the tube. The vacuum used was about one-tenth of a mm. of mercury. This sodium tube was then placed inside a Faraday magnet as shown in the figure, so that just that part of the tube containing the sodium was between the

poles of the magnet. The magnet possessed the usual Nicol prisms, one at each end, the analyzing one being provided with a rotating arm and scale which could be read to tenths of degrees. The wires from the thermo-element passed out alongside this latter Nicol and communicated with a galvanometer and two other thermo-elements, one of iron and copper and the other of constantin and copper. These two elements were placed side by side in a kerosene bath and kept at constant temperature. Directly beneath the centre of the brass tube was a Bunsen burner, the height of which was so regulated as to produce the required temperature of the vapor, as determined by the scale-reading of the galvanometer. The brass tube served to distribute the heat from the flame more evenly than could otherwise have been done, on all sides of the sodium tube, and by this means the vapor was kept at a very uniform density. When the flame is turned on, the sodium in the bottom of the tube soon melts and one might at first expect that not only would the melted sodium spread out over the entire length of the tube but that the vapor also would soon fill the entire tube. This, however, is not the case. Contrary to the behavior of most substances the melted sodium remains of practically constant length and the vapor, instead of diffusing through-out the tube, as would most gases, re-

mains immediately over the melted sodium somewhat like a viscous cloud. That the vapor does remain of practically constant length is evident from the fact that after repeated heating and cooling of such a tube, the sodium does not condense outside its initial position in the tube. Thus throughout the experiment, the column of sodium vapor remained at fairly constant length, density and temperature.

A 110-volt circuit was connected to the magnet through a double-knife switch, rheostat and ammeter. Since the magnet coils were made of very large wire, a heavy current could be used and the rheostat was adjusted until the current was 35 amperes, and all the observations were made with this current through the magnet. This current, of course, heated the magnet somewhat, but after a short time this heating became fairly steady and with a constant current, the variation in the field-strength introduced no more error than the errors of observation. The strength of the field was determined by measuring the rotation for D light which a tube of carbon bisulphide, 3.2 cm. in length, produced. The average rotation obtained was 16°.0. Assuming 0.042 in minutes of arc as the value of Verdet's constant, this rotation of 16° corresponds to a field strength of 2790 C. G. S. units.

Considerable difficulty was experienced in trying to obtain a sufficiently intense beam of light. This light had to pass through various optical parts and also the dense vapor so

that finally only a small percentage of the incident light succeeded in getting through the apparatus. As first tried, the light from an arc was brought to a focus just in front of the polarizing Nicol and after passing through this and the sodium vapor, it could be completely extingusihed by the analyzing Nicol. . Just in front of the analyzing Nicol was placed a transmission grating of 14000 lines and when the Nicols were parallel, a bright spectrum was produced in the first order. When the Nicols were crossed, the spectrum entirely disappeared. The sodium was now slowly heated and with the Nicols parallel, the D absorption band slowly appeared becoming wider and wider as the vapor became denser. Also the spectrum was displaced in a direction perpendicular to its length on each side of the D band, in opposite directions. This anomalous effect was very marked and easily explained if it be remembered that at first, the sodium vapor is not of uniform density, but densest at the bottom and most rare at the top of the tube. The vapor then acts like a prism and thus the effect of crossed prisms is obtained. This anomalous displacement, however, soon disappears as the tube becomes more evenly heated and after about ten minutes heating, the spectrum is straight through

out its length. Care was always observed not to begin observations on the rotation until the spectrum was straight.

The Nicols were now crossed and when the current was turned on, the light was immediately restored for quite a distance from each side of the D absorption band. It also seemed as if there were some light restored in part of the spectrum corresponding to the position of the red channel bands but it was not possible to be sure, with this arrangement of the apparatus. If the analyzing Nicol was now slowly turned in a direction which indicated a positive rotation there appeared two broad black bands, one on each side of the D band. As the Nicol was rotated more and more, these bands narrowed up and moved closer and closer to the edges of the D band, until finally they reached it. This showed that the rotation was positive on both sides of the D band and by the readings of the Nicol, it was seen that the rotation was very great close to the edges of the D band, but that it rapidly decreased for points further and further away. By using less dense vapor and a reflection grating mounted on a spectrometer, it was possible to see in the second order that the rotation was also positive between the two D lines, but the light here was too faint to permit a very accurate determination of its amount.

It was now necessary to devise some means of determining the wave-length cut out by the black band as the Nicol was rotated. To effect this, the light from the arc was focussed on a slit and then made parallel by a collimating lens before it passed through the first Nicol. After emerging from the second Nicol, it then fell upon a plane reflection grating and into the telescope of the spectrometer. Then the light from a Helium tube and a Mercury tube was sent through at the same time, by means of a small right-angled prism placed on the slit of the collimator, with the intention of using their characteristic lines as reference points from which to measure wave-lengths. But it was found impossible to make the lines appear sufficiently bright and the use of these tubes was abandoned.

Next the sunlight from a heliostat was substituted for the arc, with the hope that the Fraunhofer lines might be sharp enough to be used. But these too, proved to be too indistinct to be employed.

The next method tried was the following; sunlight was focussed on the slit of a Monochromatic Illuminator and light of the desired wave-length then transmitted through the first Nicol, the sodium and the analyzing Nicol in turn. Then

the latter was rotated until the light appeared to the eye, to be entirely extinguished. By this means the rotation for different wave-lengths was obtained at some distance on either side of the D band, but when settings were made up near it, the source of light could not be made monochromatic enough, even with the slits of the Monochromatic Illuminator very narrow, since the magnetic rotation in this vicinity is very great, and although the Nicol might be turned so as to extinguish light of one wave-length, light of other wave-lengths would still pass through. With this arrangement, however, the rotation was measured for wave-lengths rather distant from the D band and readings were taken until the restored light became too feeble to make the settings accurate.

For the vicinity of the D band another method was found which proved very staisfactory. The sunlight was concentrated by a large convex lens and then made parallel by a smaller lens. This parallel beam was then sent through the Nicols and sodium tube and focussed upon the slit of a two-prism spectroscope which possessed a resolving power sufficient to separate the D lines. By this means the Fraunhofer lines were in sharp focus. An auxiliary scale reflected into the field of view, appeared superposed on the solar spectrum.

The positions of some of the principal lines were determined. These positions along with the calibration curve are given below.

Calibration of Steinheil Spectroscope.

Line	Wave-length	Scale-Reading.
a	.7185 μ	0.20
B	.6870	1.10
C	.6563	2.20
D_2	.5890	5.30
E_1	.5270	9.45
b_1	.5184	10.20
F	.4861	13.35

Calibration of Thermo-elements.

Average temperature cold junction, 30.0° C.

Hot junction in melted tin, temp. 232°; average deflection, 12.5

" " " " zinc, " 419°; " " 24.1

" " " " aluminium," 657°; " " 3[illegible]

Temperature of the Sodium Vapor.

Galvanometer scale readings during experiment.

28.0

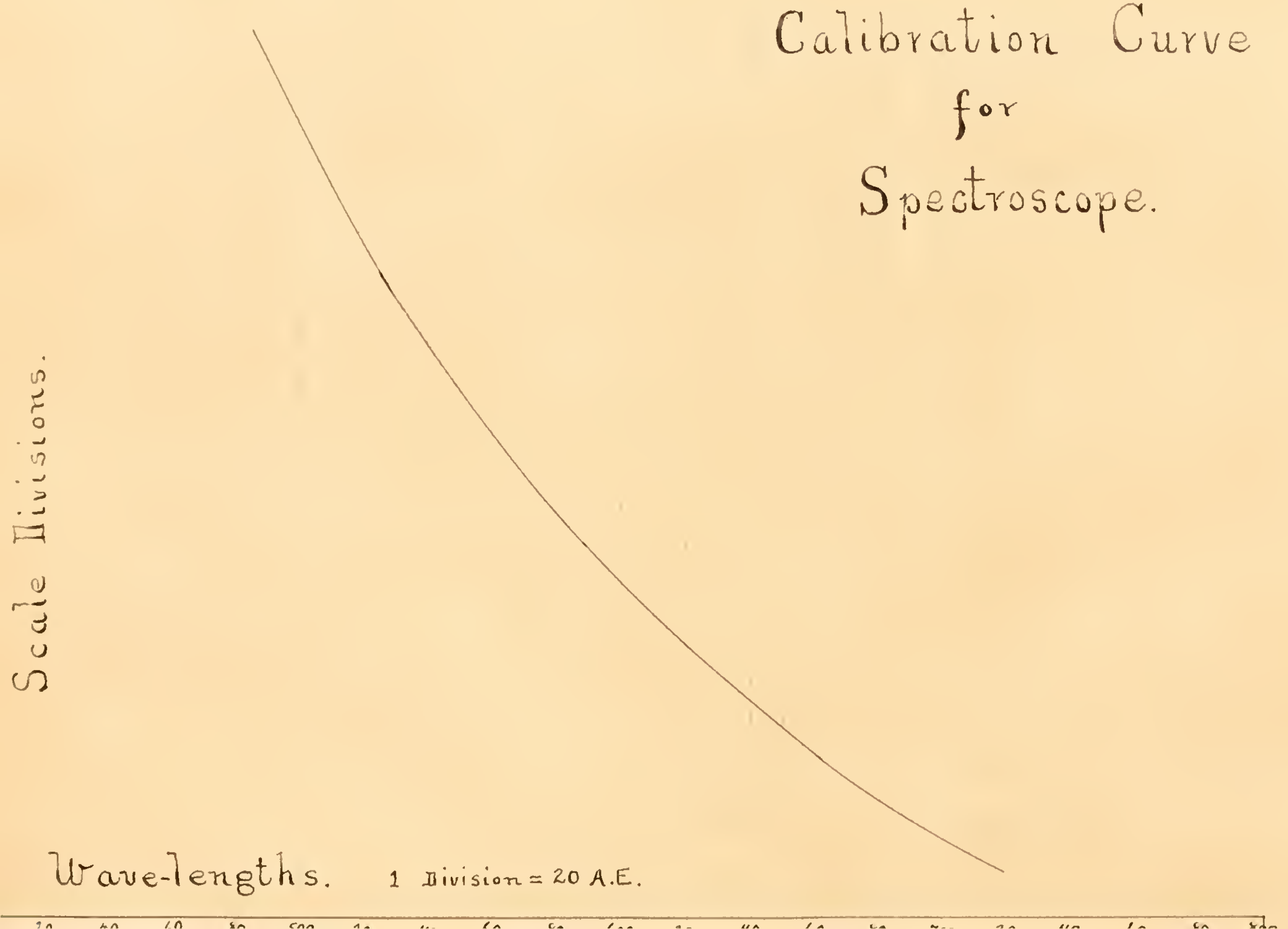
27.6

28.1

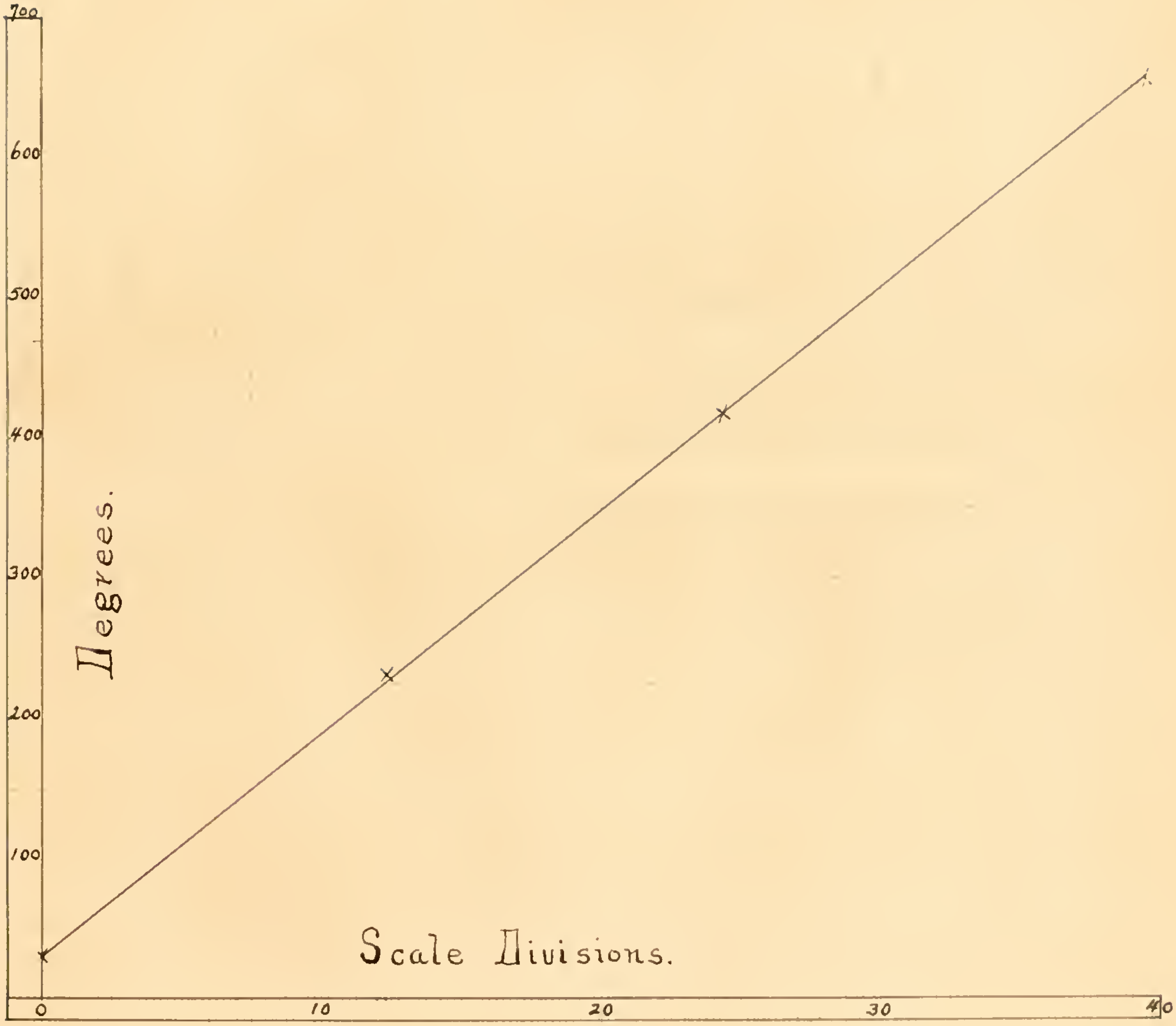
27.7

27.6

Average 27.8 Temp. of Vapor = 470° C.



Calibration Curve
for
Spectroscope.



Calibration Curve

for

With the Nicols parallel and the vapor of the right density, not only was the D absorption band visible, but also the red and blue absorption bands were very strong. Now when the Nicols were crossed, the field was dark but when the current was turned on, the spectrum brightened up, not only on each side of the D band gradually shading off in intensity, but also in the red and blue. As many as eight distinct red, and eight blue,bright bands were counted. These bright bands were contiguous with the red and blue absorption bands of sodium vapor and since the normal rotation of the vapor was too small to be detected by the method of crossed Nicols, the appearance of these bright red and blue bands showed conclusively that the red and blue absorption bands have also a very marked effect on the magnetic rotation.

When now, the Nicol was slowly rotated positively, the black bands, mentioned before, slowly crept up to the D band and any wave-length desired could be cut out on each side of the D band, but it was impossible to cut out the red or the blue light. Great care was used and the trial made over and over again to endeavor to measure the rotation in these parts of the spectrum. The Nicol was rotated very slowly through

small and large angles, both positive and negative, but the red and blue light could not be extinguished, however the Nicol was rotated. It seems probable that where apparently was a bright red band, say, there were in reality a great many wave-lengths close together and that when the Nicol was in a position to cut out one wave-length, the light from the adjacent wave-lengths masked the effect, owing to the small resolving power of the spectroscope.

The bright blue bands due to magnetic rotation were much fainter than the red and it was noticed that when the vapor was of the right density, the bright red bands might be present, but not a trace of a blue band visible. This indicates that the rotation is greater for those bright red bands than for the blue ones.

The Nicol was rotated and the position of the black bands noted with reference to the spectroscope scale. The position of the Nicol was read and the temperature of the vapor recorded. The readings were always taken with a constant current through the magnet. Throughout the experiment the temperature of the vapor remained very constant as will be seen by the galvanometer readings.

The D absorption band extended from 5.10 to 5.45 on the spectroscope scale, or from wave-length 5930 to 5870 corresponding to a difference of 60 Ångström units. The black band is very sharp and narrow up close to the D band, its width being about 0.5 of a scale-division, but proceeding away from the absorption band, it gradually widens out and becomes less sharply defined at the edges. As explained above, use was made of this band starting from the D band and moving out as far from each side of the D band as possible while the remainder of the rotations were determined with the Monochromatic Illuminator.

The rotations for the edges of the D band were obtained by gradually rotating the Nicol and turning the current on and off until no motion of the edge of the D band could be perceived. This setting could be made with an error not greater than two per cent and the mean of the readings is probably not out much more than one per cent. It will be seen on referring to the table below, that the highest rotation obtained on the red side of the D band, was + 69°.7 for wave-length 5930 and the highest on the blue side, + 107°.6 for wave-length 5870. In other words, at a distance of 34 Ångström units from D_1, towards the red the rotation was +69°.7 , and at

a distance of 20 Ångström units from D_1 towards the blue the rotation was +107°.6.

Table I gives the readings taken with the spectroscope, table II, those with the Monochromatic Illuminator, while table III gives a summary of the two.

During the experiment, a very curious effect was noticed. With the vapor very dense and the Nicols crossed, the current was turned on and the light in the different parts of the spectrum was restored as mentioned above. When now the current was broken, the yellow light on each side of the D band persisted for quite a while after. The time of this persistence was about two or three seconds. In order to be sure that this was not due to any physiological effect, the current was turned off and the eye placed, a second or two later at the telescope, could still see the persistence of this light. Two explanations are possible. Either the magnetic field persisted for two or three seconds after the current was shut off, or there was set up in the sodium vapor some state which continued for this length of time after the current was broken. As mentioned above, sodium vapor acts like a viscous gas, if one may use the term, and it is just possible that the latter

Table I.

Rotation with Spectroscope.

Length of Vapor = 8.2 cm. Temperature of Vapor = 470°.C.

Strength of Field =2790 C. G. S. units. Zero of Nicol = 11°.0 .

Spectroscope Scale		Wave-lengths.	Nicol Readings I.	II.	III.	Rotations. 1.	II.	III.	Av. Rotation in degrees.
4.70		6005	14.0	14.1	13.8	3.0	3.1	2.8	+ 3.0
4.80		5985	16.8	16.1	16.5	5.8	5.1	5.5	5.5
4.90		5965	20.5	20.6	20.8	9.5	9.6	9.3	9.6
5.00		5950	33.0	32.8	33.1	22.0	21.8	22.1	22.0
5.10		5930	80.0	81.2	80.8	69.0	70.2	69.8	69.7
5.25	D_1	5896							
5.30	D_2	5890							
5.43		5870	117.6	119.0	119.2	106.6	108.0	108.2	107.6
5.50		5855	34.2	34.5	34.6	23.2	23.5	23.6	23.4
5.60		5835	21.6	21.8	22.0	10.6	10.8	11.0	10.8
5.70		5820	17.5	17.4	17.7	6.5	6.4	6.7	6.5
5.80		5805	15.4	16.1	15.8	4.4	5.1	4.8	4.8

Table II.

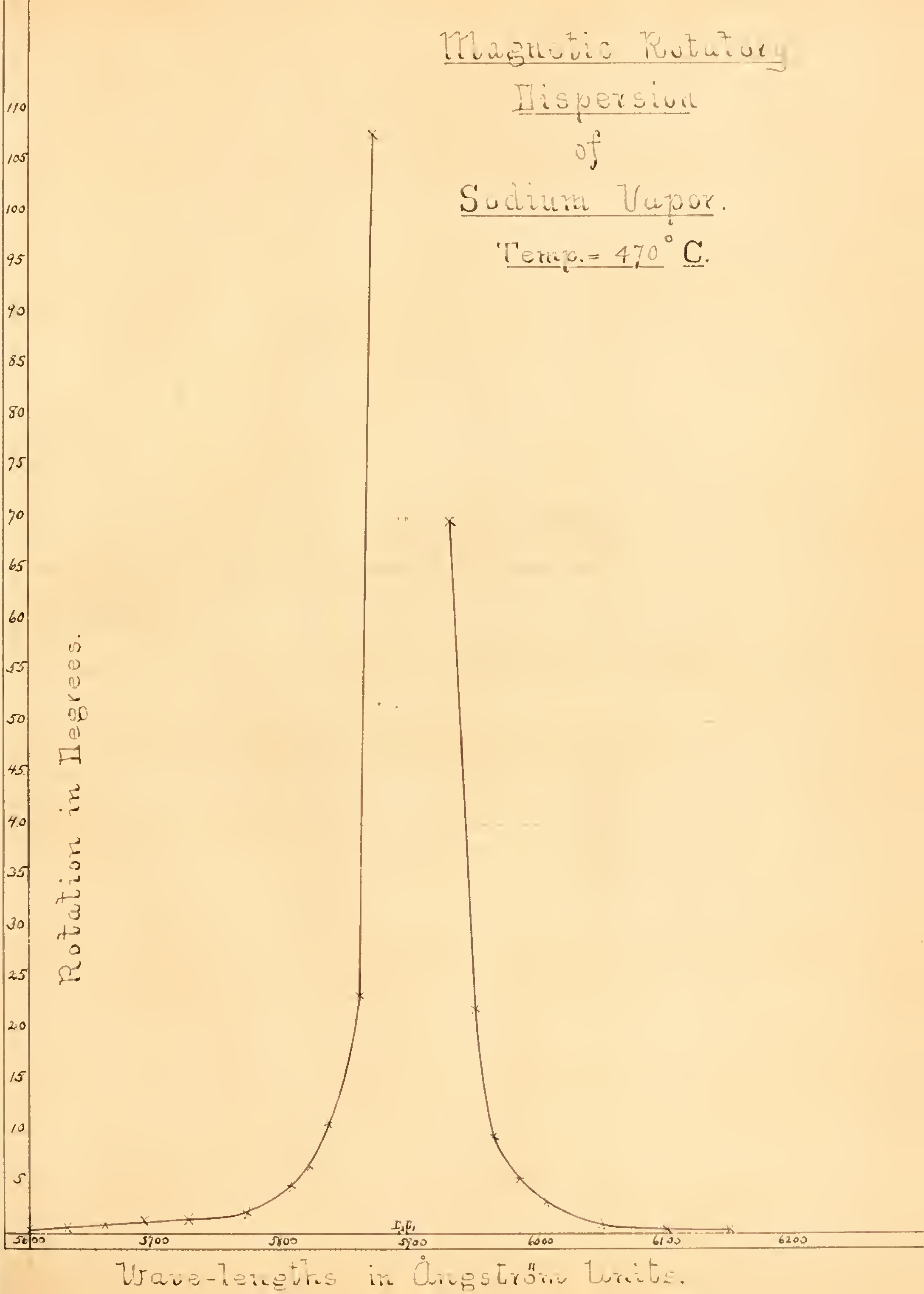
Rotation with Monochromatic Illuminator.

Illuminator Scale	Wave-lengths	Nicol Readings I.	II.	III.	Rotations I.	II	III.	Av. Rotations in degrees.
9.40	6350	11.3	11.3	11.2	0.3	0.3	0.2	+ 0.3
9.35	6100	11.4	11.4	11.5	0.4	0.4	0.5	0.4
9.30	6050	11.8	11.8	11.7	0.8	0.8	0.7	0.8
9.25	6010	13.7	13.6	13.8	2.7	2.6	2.3	2.7
8.95	5770	13.2	12.8	12.9	2.2	1.8	1.9	2.0
8.90	5725	12.5	12.4	12.3	1.5	1.4	1.3	1.4
8.85	5690	12.2	12.2	12.1	1.2	1.2	1.1	1.2
8.80	5660	12.0	12.1	12.0	1.0	1.1	1.0	1.0
3.75	5630	11.6	11.6	11.7	0.6	0.6	0.7	0.6
8.70	5600	11.[illegible]	11.4	11.3	0.5	0.4	0.3	0.4

Table III.

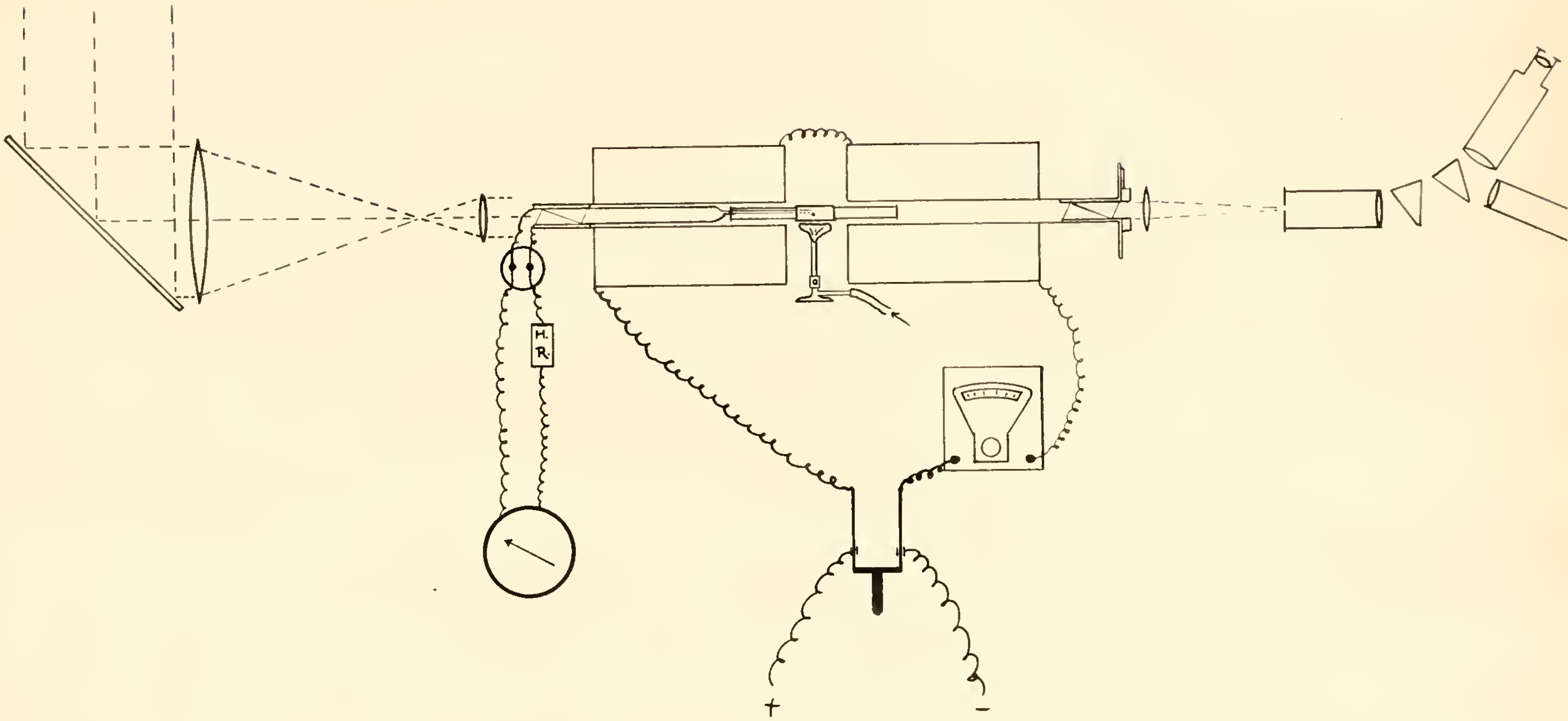
Rotations from Wave-lengths 6150 to 5600.

Wave-length	Rotation in degrees.
6150	+ 0.3
6100	0.4
6050	0.8
6010	2.7
6005	3.0
5985	5.5
5965	9.6
5950	22.0
5930	69.7
D_1 5896	
D_2 5890	
5870	107.6
5855	23.4
5835	10.8
5820	6.5
5805	4.8
5770	2.0
5725	1.4
5690	1.2
5660	1.0
5630	0.6



Magnetic Rotatory Dispersion of Sodium Vapor.

Temp. = 470° C.



Arrangement of Apparatus.

is the true explanation. It hardly seems possible that the magnetic field could persist for so long a time, and yet, reasoning from the phenomena of fluorescence and phosphorescence, it would be surprising if the sodium vapor required so much time to recover its normal state. It is possible that by using a helix of many turns of wire, with no iron and a very heavy current, the point could be decided. But it is rather doubtful whether one could thus obtain a field anything like as strong as with the iron. If this method failed, possibly a flip-coil might be used between the magnet poles to determine how long it takes for the magnetic field to die down.

CONCLUSIONS.

Three theories have been advanced to explain magnetic-rotation; (1) the theory based on the hypothesis of molecular currents[17]. This theory presupposes that in para-magnetic substances there are molecular currents due to the motion of the ions in circular orbits and that these molecular currents are partially or wholly turned into such a direction that the magnetic lines due to them are superposed upon the lines due to the external field; in diamagnetic substances, however, there are ordinarily no such currents. But as soon as they are brought into a magnetic field, they have induced in them, molecular currents, the magnetic lines of which, are directed against the external field. If now the ion producing this molecular current be acted on by the electric force of a light wave, the point around which it rotates is shifted. This displacement of the molecular current thus gives rise to a displacement of the magnetic lines of force. This leads to the conclusion that the rotation should have a different sign on the two sides of an absorption band. This prediction was verified by Schmauss'[18] experiments, for he obtained opposite ro-

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[17] See Drude's Optics, Eng. Trans. p. 418.
[18] Schmauss, l. c.

tations on each side of the band; (2) the theory on the basis of the "Hall Effect"[19]. Here it is assumed that we have movable but not rotating ions. Since an ion in motion represents an electric current, it will as a result of the "Hall Effect", when placed in a strong magnetic field, experience a force which is perpendicular to the element of current and the direction of magnetization. Hence, in a magnetic field the current lines tend to move in a direction at right angles to their direction. This theory leads to just the opposite conclusion of (1), i. e., the rotation should have the same sign on both sides of the band. This has been verified in the case of sodium vapor by the work of Zeeman[20], Macaluso and Corbino[21] and by the present experiment; (3) the theory advanced by Voigt[22] shows that in the vicinity of the band and at the same distance from each side of it, the rotation should have the same sign and magnitude; a later addition[23] to this theory shows that a negative rotation should be expected inside the band, about equal in absolute value to the positive rotation just at the outer edge. The experiments of Macaluso and Corbino were in contradiction to this since they obtained a

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[19] See, Drude's Optics, p. 433.
[20] Zeeman, l. c.
[21] Macaluso and Corbino, l. c.
[22] Voigt, Ann. d. Phys. u. Chem. 67, p. 345, 1899.
[23] Voigt, Ann. d. Phys. u. Chem. 6, p. 784, 1901.

small positive rotation inside the band, but the high negative rotation observed by Zeeman seems to confirm this part of the theory. According to this theory the maximum rotation near the band should be independent of the field strength and the negative rotation inside should decrease as the field increases. Schmauss' experiments seemed to have verified this point.

While previous experiments with sodium vapor have had to do with the rotation very close to the D lines, the present method has permitted the measurement of this rotation over a considerable range, from wave-length 6150 to wave-length 5600 and has also established the fact that, not only does the D absorption band greatly influence this rotation but that the strong absorption bands in the red and blue have also a very marked effect. With a much higher resolving power it might be possible to measure their rotatory effect also.

I am deeply grateful to Professor Ames, Professor Wood and to my fellow-student Mr. A. H. Pfund, for their generous assistance in carrying out the above work.

BIOGRAPHY.

Harry William Springsteen was born February 25, 1875 in Pittsburgh, Pennsylvania, and was prepared for college in the public schools of Cleveland, Ohio. Entering the Case School of Applied Science in September 1892, he was graduated from that institution in 1897 with the degree of Bachelor of Science having held a Scholarship for the five years. He was then appointed Instructor in Physics there, and continued in that position until June 1902. In 1900 he received the degree of Master of Science from Case School and during the year 1901 pursued graduate work at the Western Reserve University from which he received the degree of Master of Arts.

In the fall of 1902 he entered the Johns Hopkins University taking Physics as his principal subject and Physical Chemistry and Mathematics as his two subordinate subjects, respectively. During the past year he held a University Scholarship.

During his connection with this University he has followed the lectures of Professor J. S. Ames, Professor R. W. Wood, Dr. J. B. Whitehead in his principal subject, and the lectures of Associate Professor Harry C. Jones and Dr. A. Cohen in his

two subordinate subjects. To all these gentlemen he extends his sincerest thanks for their guidance and instruction.